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BLE or IEEE 802.15.4: Which Home IoT Communication Solution is more Energy-Efficient?

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Abstract

IEEE 802.15.4 (used by Zigbee, 6LoWPAN and Thread) and Bluetooth Low Energy (BLE) are two widely used wireless standards for ultra low power IoT (Internet of Things) technologies and smart home applications. In this article, we present the first comparison of the physical layer of the two protocols, focusing on two performance metrics: energy efficiency and wireless coverage. The comparison uses the first radio that seamlessly supports both protocols; therefore, the protocols are compared on identical hardware and software. By combining the two metrics, we quantify the performance, and identify in which types of links it is preferable to use one protocol or the other, thus providing practical guidelines to developers of short-range energy-constrained wireless networks and smart home applications.

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1. Introduction

Advances in sensor technologies and low power electronics have enabled the realisation of the Internet of Things (IoT). The applications are numerous, including smart cities [23], smart buildings [22], wearable computers [3], metering infrastructures [14], ambient assisted living [18], and healthcare technologies [7]. Energy-efficient communications is generally considered a fundamental challenge for the realisation of viable IoT technologies, which are typically powered by batteries. Indeed, the more sensing technologies become ubiquitous, the higher the maintenance cost of replacing or recharging batteries. Energy harvesting is widely considered an alternative to batteries [9][10]. Nevertheless, in most scenarios, the energy that can be harvested is very limited [19]; thus, energy-efficient communications remain a vital part of the system design [6].

After more than a decade of ongoing research in energy-efficient protocols and networks [17][8], sensing technologies primarily build upon two basic standards, namely IEEE 802.15.4 and Bluetooth Low Energy (BLE), along with some additional proprietary solutions. IEEE 802.15.4 [1] is a standard for wireless personal area networks, and defines the physical (PHY) and Medium Access Control (MAC) layers of the protocol stack. It is the basis of 6LoWPAN and various higher layer protocol suites, including Zigbee [24] and the recently-announced Thread [21]. Furthermore, the physical layer of IEEE 802.15.4 is frequently used in Contiki, the operating system for IoT (for example, see the implementation of IPv6 multicast forwarding over IEEE 802.15.4 in [16]). On the other hand, BLE [2] traces its roots in the IEEE 802.15.1 standard for short-range “cable replacement" applications. BLE is a standard for wireless personal area networks that is typically supported by laptops and smart phones. In addition to fitness, healthcare and home entertainment applications, it is also the basis of the iBeacon protocol [15] that is targeted for location-based services.

The wide availability of both IEEE 802.15.4 and BLE solutions raises the question of which approach is preferable to use in a particular application. We experimentally address this question from the perspective of

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the physical layer performance, focusing on two fundamental metrics, namely energy efficiency and wireless coverage. Our comparison extends previous findings that focus on higher layers of the communications stack [20][5][13]. According to these works BLE is more energy-efficient than ZigBee / IEEE 802.15.4. Having a different focus, however, these studies do not take into account packet loss due to channel errors. In fact, as we show in this work, because of packet loss, BLE is not always more energy-efficient than IEEE 802.15.4.

Despite the fact that they are primarily used as part of full protocol stacks, the physical layers of IEEE 802.15.4 and BLE are following a layered architecture and, thus, can be potentially isolated from their original protocol stack and used together with alternative link and network layer protocols. This constitutes a major motivation for the physical layer comparison presented in this paper. Indeed, there is a series of recent works that implement MAC and routing protocols, which are typically used with IEEE 802.15.4, on top of the physical layer of BLE [4][12]. In this context, given the same upper layer protocols, the presented work addresses the question of which is the best physical layer solution.

Moreover, we extend the literature with quantitative results on the wireless performance of the examined solutions, identifying the RSSI limits for specific PER (Packet Error Rate) requirements. Lastly, in contrast with the previous works, our performance comparison study uses the TI CC2650 system-on-chip (SoC), which is the first commercial off-the-shelf radio that seamlessly supports both IEEE 802.15.4 and BLE. As a result, the protocols are compared in test-beds that are as identical as possible, both in terms of hardware and software.

The contribution of this article can be summarised as follows. We experimentally quantify and compare the energy efficiency and wireless performance of the physical layer of IEEE 802.15.4 and BLE. The comparison is conducted using the first off-the-shelf radio that seamlessly supports both protocols, and quantifies the effect of the frame size and transmission power on the above metrics. Practical design recommendations are provided on when it is preferable to use IEEE 802.15.4 or BLE.

The remainder of the article is organised as follows. Section 2 provides a brief overview of the physical layer of IEEE 802.15.4 and BLE. Section 3 discusses the experimental test-bed and the comparison results. Lastly, Section 4 summarises the key findings and provides practical guidelines on when each protocol should be used.

2. Brief Protocol Overview

IEEE 802.15.4 defines the PHY and MAC layers of the protocol stack. Its physical layer supports both the 2.4 GHz ISM (Industrial, Scientific and Medical) band and the sub-GHz ISM bands. In the 2.4 GHz band, which is the focus of this article, it offers a nominal data rate of 250 Kbps and it is based on Offset QPSK (Quadrature Phase Shift Keying) modulation. IEEE 802.15.4 splits the 2.4 GHz band into 16 channels that are 2 MHz wide and spaced by 5 MHz. Each frame begins with a 4-byte preamble and a 1-byte start frame delimiter (SFD), which is followed by an additional byte that defines the length of the frame. A PHY payload of up to 125 bytes[1], including the respective headers, follows. The footer of the frame is a 2-byte field that contains the CRC (Cyclic Redundancy Check) value.

BLE defines a full stack of protocols, including application profiles. Its physical layer supports only the 2.4 GHz ISM band. It offers a nominal data rate of 1 Mbps and it is based on GFSK (Gaussian Frequency Shift Keying) modulation. BLE splits the 2.4 GHz band into 40 channels that are 2 MHz wide. Each frame begins with a 1-byte preamble that is followed by a 4-byte access address. A PHY payload of up to 39 bytes follows. The footer of the frame is a 3-byte field that contains the CRC value.

To summarise, BLE offers a higher nominal data rate, while IEEE 802.15.4 supports larger frames. Both protocols introduce 8 bytes of overhead at the physical layer.

3. Performance Comparison

3.1. Hardware

The comparison of IEEE 802.15.4 and BLE is conducted using two evaluation modules of the TI CC2650 SoC (CC2650EM-7ID) as a transmitter and receiver. The evaluation module is interfaced to a SmartRF06 Evaluation Board and, in terms of software, SmartRF Studio 7 is used. In this comparison study, the CC2650 system is selected primarily because it is the first off-the-shelf SoC that supports both IEEE 802.15.4 and BLE. Using the exact same hardware for repeating the experiments in IEEE 802.15.4 and BLE mode guarantees that the protocols are compared in test-beds that are as identical as possible, both in terms of software and hardware. Unless otherwise stated, all experiments are conducted in a real environment without apparent interference.

[1] The standard specifies a PHY payload of up to 127 bytes that include 2 bytes for the CRC field. To facilitate the comparison, we consider CRC as part of the PHY footer.

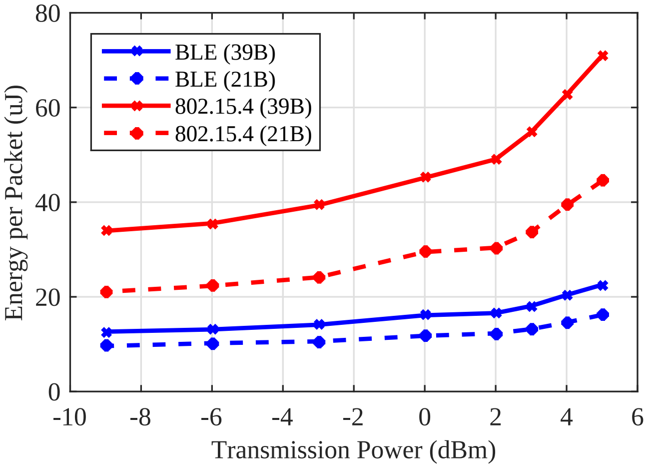

Figure 1. Energy consumption of a single frame transmission for two PHY payload sizes, and for various transmission power levels.

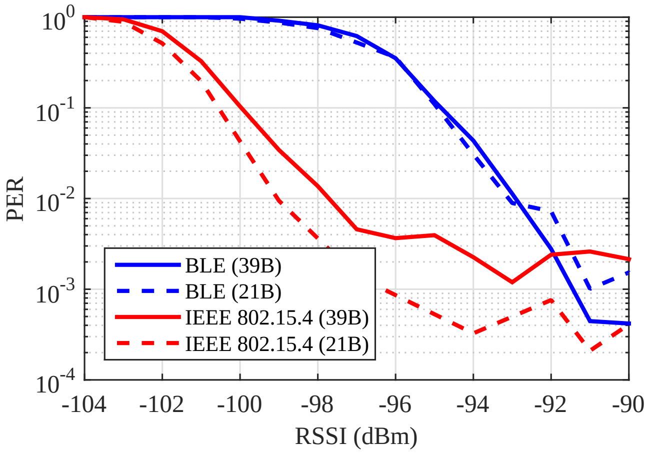

Figure 2. Empirical PER vs. RSSI curves for two different PHY payload sizes.

3.2. Energy Consumption

We begin the comparison by measuring the energy that is required to transmit a single BLE or IEEE 802.15.4 frame. The two protocols are compared for the same PHY payload sizes, $L = 21$ and $L = 39$ bytes, *i.e.* excluding the PHY headers and the CRC field. In both cases an additional 8 bytes are transmitted over the air that contain the PHY header and footer.

Fig. 1 shows the energy consumed by transmitting a single frame for various transmission power levels up the maximum level supported by the system, $P_{tx} = 5$ dBm. In the measurements, the supply voltage was regulated at $V_S = 3.3$ V. The measurements demonstrate that BLE consumes significantly less energy than IEEE 802.15.4 in all considered scenarios. The difference is primarily due to the fact that IEEE 802.15.4 needs more time to transmit the frame because of its lower data rate. Moreover, the difference of the protocols widens as the transmission power increases. This happens because of the constant energy consumed by the radio, which does not depend on the transmission power. The maximum difference is observed at 5 dBm and for $L = 39$ bytes where BLE consumes 31% of what IEEE 802.15.4 does for a single frame transmission.

3.3. Packet Error Rate

In terms of energy consumption, the superiority of BLE is apparent. Yet, in terms of wireless performance, IEEE 802.15.4 is expected to perform better. Due to the lower bandwidth (IEEE 802.15.4 operates at 256 Kbps, whereas BLE operates at 1 Mbps), IEEE 802.15.4 has a 6 dB better sensitivity at the same operating temperature [11].

In the next experiment, we quantify the wireless performance of each protocol, identifying their RSSI limits for given PER requirements. In particular, we transmit a known payload and measure the PER for various RSSI (Received Signal Strength Indicator) levels. The measurements were conducted in an indoor environment (room temperature). The receiver was fixed to a computer, while the transmitter was positioned in different locations around it. Since the measurements were conducted in a real environment, several precautions were taken to minimise the number of corrupted frames due to interference. The data collection sessions were performed using a frequency channel that did not overlap with the surrounding IEEE 802.11 access points, and only when no activity was observed in the respective channels.

Fig. 2 summarises the results, considering two PHY payload sizes, $L = 21$ and $L = 39$ bytes, similarly to the energy consumption measurements. It can be observed that IEEE 802.15.4 yields 5 dB better wireless performance on average. In particular, the 1% PER threshold for $L = 39$ bytes is approximately at −93 dBm for BLE and −98 dBm for IEEE 802.15.4. The smaller PHY payload size of 21 bytes yields better wireless performance, albeit with only a minor improvement of less than 1 dB. The 1% PER threshold for a frame of 21 bytes is approximately at −93 dBm for BLE and −99 dBm for IEEE 802.15.4. It should be noted that for lower PER thresholds (*e.g.* 10^{-3}) additional samples are required for safe comparisons.

3.4. Retransmissions

In broadcasting schemes, channel errors and corrupted frames are simply experienced as packet loss by the higher layers of the system. Unicast MAC protocols, on the other hand, typically implement link-layer acknowledgements and retransmissions to mitigate packet loss. In this case, corrupted packets are experienced in the transmitter as an additional source

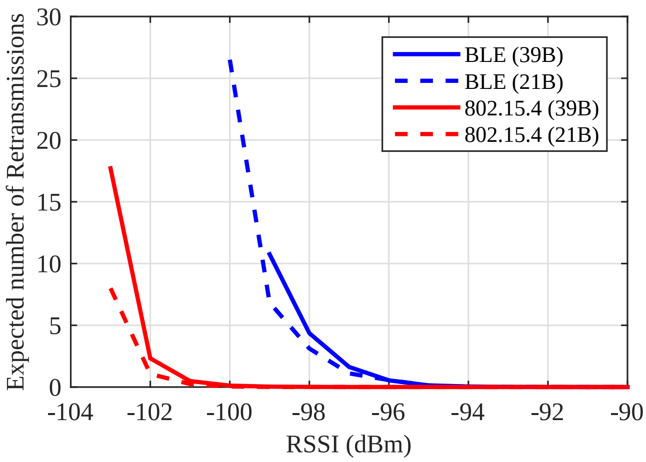

Figure 3. Estimated number of retransmissions required for the successful transmission of a single frame.

of energy consumption. The more retransmissions are required for a packet to pass through the link, the more energy is consumed.

To visualise the effect of packet loss on energy consumption, we assume that both protocols use the exact same retransmission scheme at the link layer, and we model retransmissions as a sequence of independent Bernoulli trials with the same probability of failure (*i.e.* PER) for each trial. The expected number of retransmissions, N, can therefore be calculated as

$$N = \sum_{n=1}^{\infty} n\Big(1 - p(r)\Big)p(r)^{n-1} - 1 = \frac{p(r)}{1 - p(r)}, \qquad (1)$$

where $p(r)$ is the PER for an RSSI r, as measured in Fig. 2. The expected number of retransmissions for a given PER can be used as an approximation of the energy consumption of the transmitter normalised to the energy required to transmit a single frame. Fig. 3 plots the estimated number of retransmissions given by (1) applied to the PER shown in Fig. 2. It can be observed that at low values of the RSSI an increasing number of retransmissions is required by BLE to achieve reliable communication. Below −99 dBm, the PER of BLE makes communication impossible whereas IEEE 802.15.4 can still operate with retransmissions. A dependence of the expected number of retransmissions on the PHY payload size is also observed, inherited from the PER shown in Fig. 2.

3.5. Energy Efficiency

In the previous experiments, we showed that BLE consumes significantly less energy than IEEE 802.15.4 to transmit the same PHY payload, while the latter offers a significantly better wireless performance. Furthermore, we quantified how the transmission

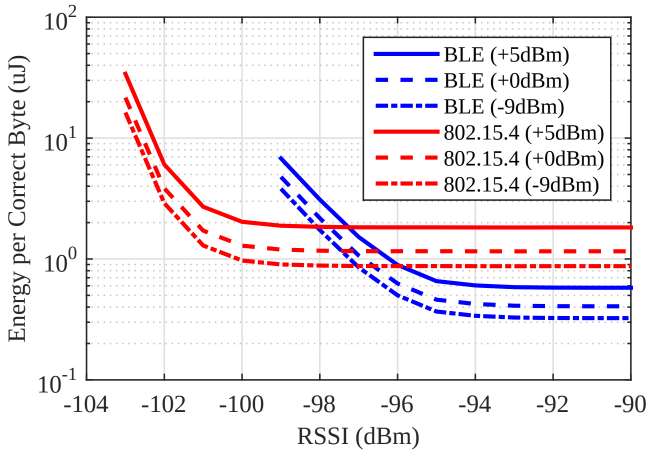

Figure 4. Energy consumption of the transmission of a successful byte (accounting for potential retransmissions) for various transmission power levels, considering $L = 39$ bytes.

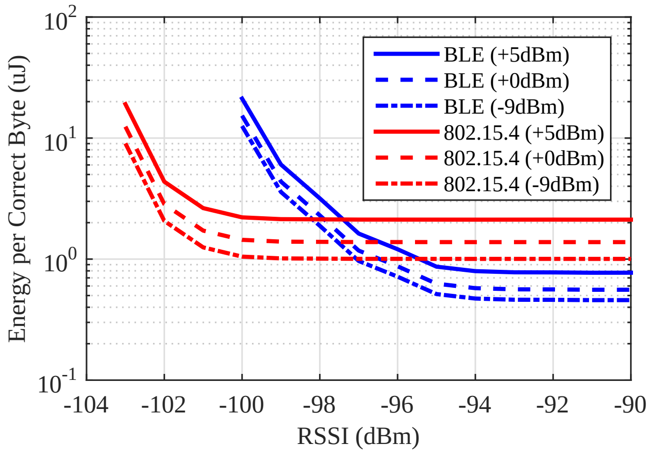

Figure 5. Energy consumption of the transmission of a successful byte (accounting for potential retransmissions) for various transmission power levels, considering $L = 21$ bytes.

power and the frame size affect the energy consumption and the PER. More specifically, the transmission power offers a better wireless performance at the cost of additional energy consumption, and smaller frame sizes offer lower energy consumption and lower error probability rates at the cost of a lower throughput. In this section, we put everything together in an attempt to identify when, overall, BLE performs better than IEEE 802.15.4 and vice versa.

For this purpose, we define the long-term energy efficiency, η, as the long-term average energy required to successfully transmit a single PHY payload byte. Building upon the measurements presented in the previous sections, it is calculated by dividing the total energy required for a frame transmission by the long-term average number of correctly received bytes. This is shown in equation (2), where $E_{L,P_{tx}}$ is the energy consumed for a given PHY payload size L and transmission power P_{tx} as illustrated in Fig. 1, and $p(r)$ is the PER for an RSSI r, given by Fig. 2.

$$\eta = \frac{E_{L,P_{tx}}}{L\big(1 - p(r)\big)} \qquad (2)$$

Fig. 4 plots the results for the larger PHY payload size, $L = 39$. It can be observed that, in every case, there is a threshold that identifies which protocol performs better. For example, in the case of $P_{tx} = 5$ dBm, BLE yields better energy efficiency per correct byte when the average RSSI is −97 dBm and above, while IEEE 802.15.4 yields better energy efficiency per correct byte when the average RSSI is −98 dBm and below. It can also be observed that as we decrease the transmission power level, the threshold moves slightly to the right, indicating that IEEE 802.15.4 benefits more from this reduction. The smaller PHY payload size, $L = 21$, shown in Fig. 5, demonstrates similar patterns. Comparing the absolute values, the larger payload size offers a slightly better energy efficiency per correct byte, in both protocols. This is caused by the constant energy consumption overheads of the electronics and the physical layer.

The results, therefore, suggest that it is preferable to use BLE for links that are characterised by high RSSIs. In the case of links that operate close to the sensitivity threshold, on the other hand, it is preferable to use IEEE 802.15.4. In a practical deployment with fixed links, Fig. 4 can be used along with a propagation model or empirical propagation measurements, to determine the most efficient solution.

3.6. Mobility

Fig. 4 demonstrates that BLE is more energy-efficient than IEEE 802.15.4 at all RSSI values apart from the range from −103 dBm until approximately −98 dBm. In this section, we consider an indoor residential environment with mobile nodes, and we incorporate the probability that the RSSI is within these levels.

For this purpose, we collect RSSI measurements in a real residential environment with thick brick walls, as shown in Fig. 6. Two application scenarios are considered: applications that require single-room coverage, and applications that require full-house coverage. In both cases, we fix the receiver (Rx) in one of the rooms, *i.e.* the lounge. For the single-room scenario, the mobile transmitter (Tx) is positioned in the same room. For the full-house scenario, the mobile transmitter is positioned in a room that is separated by two walls from the receiver, *i.e.* the kitchen, which is a typical worst case scenario for residential environments of that size. In each of the considered rooms, a user performs random walks for approximately 5 minutes holding the transmitter node that transmits frames of

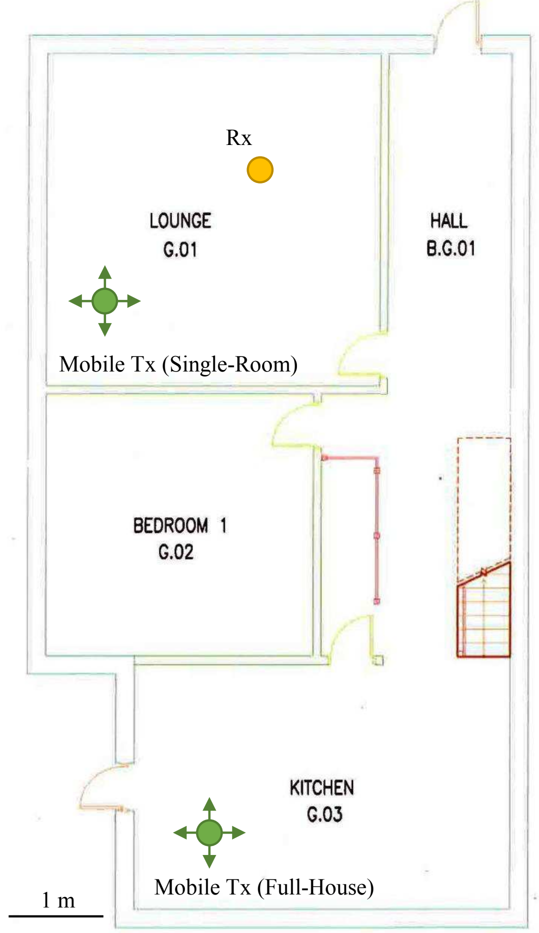

Figure 6. Mobility is evaluated in a real residential environment. Two application scenarios are considered: in the single-room scenario the mobile transmitter (Mobile Tx) performs random walks in the same room with the receiver (Rx); in the full-house scenario the mobile transmitter performs random walks is a room that is separated by two walls from the receiver.

$L = 39$ bytes at $P_{tx} = 5$ dBm. Considering mobility and the statistical distribution of the RSSI r, the energy efficiency per byte, η, of (2) can be rewritten as follows:

$$\eta = \frac{E_{L,P_{tx}}}{LK}, \quad \text{where} \quad K = \sum_{r=-110}^{0} q(r)\big(1 - p(r)\big). \qquad (3)$$

In (3), $q(r)$ is the probability of the reception of a frame with an RSSI of r, and it is obtained empirically by measuring the statistics of the collected RSSIs. Given statistics on the RSSI within a room, K is the average reception probability of a frame when the transmitter is inside the particular room.

Fig. 7 plots the CDFs of the RSSIs of the measured scenarios. In the case when the mobile transmitter is in the same room with the receiver (single-room coverage), it can be seen that the RSSI values, seen by the receiver,

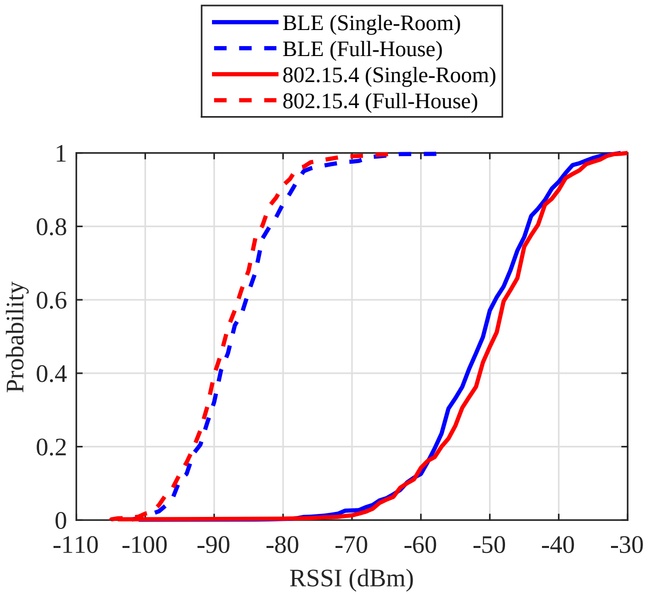

Figure 7. Empirical CDF of the RSSI when the transmitter and the receiver are in the same room (single-room coverage) and separated by two walls (full-house coverage).

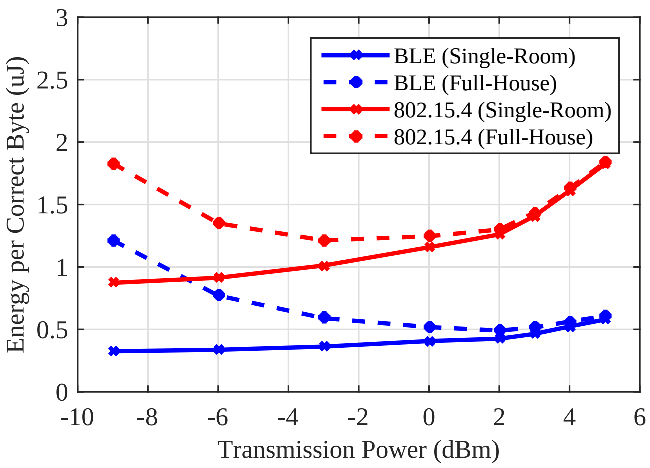

Figure 8. Energy efficiency for various transmission power levels when the transmitter and the receiver are in the same room (single-room coverage) and separated by two walls (full-house coverage).

range from −80 dBm to −30 dBm with −50 dBm being the median case. In the case of random walks in the room that is separated by two walls (full-house coverage), a larger portion of the frames are received at low RSSIs. The RSSI values, seen by the receiver, range from −105 dBm to −65 dBm with −88 dBm being the median case. Considering that the path loss is independent of the transmission power, the respective RSSI values of a lower transmission power setting can be derived by subtracting the relative difference from each collected RSSI sample. This results to a CDF that is shifted to the left by that difference. For example, for $P_{tx} = 0$ dBm the CDF is shifted by 5 dB to the left.

In Fig. 8, we use the statistics shown in Fig. 7 on (3), while shifting them appropriately to take into account different transmission power levels. In can be observed that for short links within a residential room, the received power levels are so high that almost no retransmissions are required. Therefore, BLE is overall more energy-efficient than IEEE 802.15.4, in line with what is expected from Fig. 4. In fact, the RSSIs are so high that reducing the transmission power improves the energy efficiency of both protocols. At low transmission power levels, a larger portion of the frames are received in the range of RSSIs where IEEE 802.15.4 performs better. Hence, the difference between the energy efficiency of the protocols becomes smaller at those power levels. For applications that require full-house coverage (transmitter and receiver separated by two walls), the energy efficiency of both protocols reaches an optimum value beyond which reducing the transmission power decreases the overall energy efficiency, as more frames require retransmissions. IEEE 802.15.4 reaches the maximum energy efficiency per byte ($\eta = 1.21$ μJ) at $P_{tx} = -3$ dBm and BLE reaches the maximum energy efficiency per byte ($\eta = 0.49$ μJ) at $P_{tx} = 2$ dBm.

Mobility introduces links with a very high dynamic range of RSSIs. Despite the fact that IEEE 802.15.4 is more energy-efficient in links that operate very close to the sensitivity threshold, in a mobile scenario, BLE is overall more energy-efficient, as the mobile transmitter is statistically more likely to be in the range where BLE yields higher efficiency.

3.7. Interference

Lastly, we discuss the resilience of the examined protocols to interference. It can be observed from the standards (see Section 2) that IEEE 802.15.4 splits the band into only 16 channels providing some guard space against adjacent channel interference. On the other hand, BLE splits the band into 40 channels, without providing any guard space between them. Nevertheless, we experimentally verified that BLE does not suffer from adjacent channel interference. The experiment was performed in an anechoic chamber as follows. A sender node and an interferer node are positioned at a 1-meter distance from the receiver. Whilst the sender node is transmitting packets at a constant rate (10 Hz) to the receiver node on a fixed channel, the interferer node transmits traffic at the same rate in the adjacent channels. Both nodes transmit at the maximum transmission power. In this setting, no packet loss was recorded due to adjacent channel interference. Therefore, we can conclude that BLE offers a significantly higher number independent channels to the higher layers, allowing a higher utilisation of the band and a larger amount of overlapping interference-free links.

4. Discussion and Concluding Remarks

IEEE 802.15.4 and BLE are two widely adopted wireless standards for IoT applications and ultra low power networks. Both standards are widely supported by radio manufacturers with a variety of commercial off-the-shelf options. From the perspective of the physical layer, in this article we address the question of which solution is better to be employed in a particular application.

To guarantee fairness, the comparison is conducted using the TI CC2650 SoC that is the first commercial off-the-shelf radio that supports both IEEE 802.15.4 and BLE. Thus, the comparison is conducted using test-beds that are as identical as possible both in terms of the hardware used for the transmitter and the receiver, and in terms of the firmware implementation and supporting tools.

The findings of the comparison are summarised as follows:

- *BLE consumes less energy than IEEE 802.15.4 to transmit a single frame.* The difference between the protocols increases as a higher transmission power or a larger PHY payload size is used. At a transmission power of $P_{tx} = 5$ dBm and at a PHY payload size of $L = 39$ bytes, IEEE 802.15.4 consumes approximately 3 times more energy to transmit a single frame.

- *IEEE 802.15.4 provides wider wireless coverage than BLE.* An approximately 5 dB difference is empirically measured. The 1% PER threshold for a PHY payload size of $L = 39$ bytes is at −98 dBm for IEEE 802.15.4 and −93 dBm for BLE. The payload size minimally affects the wireless performance.

- *There is an RSSI threshold below which IEEE 802.15.4 yields a higher energy efficiency per correctly received byte than BLE and vice versa.* After incorporating the probability of packet loss due to channel errors, at $P_{tx} = 5$ dBm, BLE yields better energy efficiency per correct byte when the average RSSI is −97 dBm and above, while IEEE 802.15.4 yields better energy efficiency per correct byte when the average RSSI is −98 dBm and below. Hence, in the case of static links that operate very close to the sensitivity threshold, it is more energy-efficient to use IEEE 802.15.4; otherwise, BLE offers a higher energy efficiency.

- *In mobile indoor scenarios, BLE is on average more energy-efficient than IEEE 802.15.4.* Measurements in a real residential environment show that it is statistically more likely for a mobile transmitter to operate in the range of RSSI where BLE yields higher efficiency, both in mobile applications that require single-room coverage and applications that require full-house coverage.

- *BLE offers a higher number of orthogonal channels.* Experiments have verified that BLE does not suffer from adjacent channel interference. Hence, in contrast to IEEE 802.15.4, BLE supports a larger amount of overlapping interference-free links / networks.

To conclude, it is important to stress that the presented comparison focuses only on the physical layer of the protocol stack. The overall energy efficiency of a wireless stack also depends on the performance of the higher layer protocols. We refer the reader to related works [20][5][13] that present comparisons at a higher layer. Furthermore, in some situations, the selection of the protocol may solely depend on the compatibility with other platforms. Although both IEEE 802.15.4 and BLE are typically used as a full stack, it is important to note that their physical layer can be isolated and used with protocols outside the standardised stacks for a tailored solution that suits the needs of a given application.

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